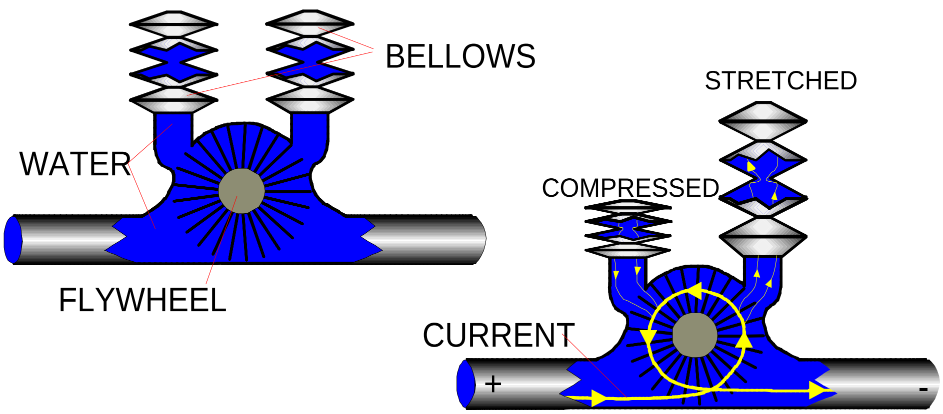
INDUCTORS

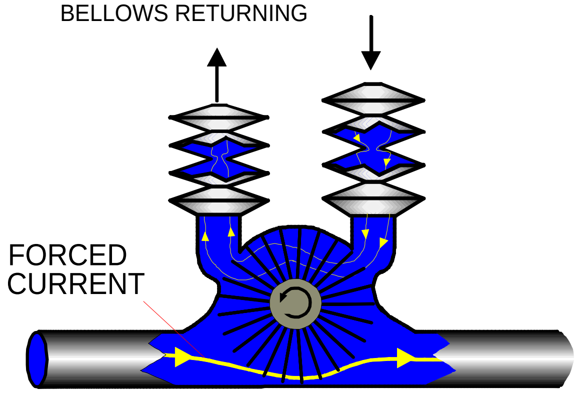
INDUCTANCE IN WIRES

When a conductor has a current passing through it, a magnetic field is produced around the conductor. When the current in the conductor varies, the resulting changing magnetic field induces a voltage in the conductor opposite to the applied voltage and tends to limit or reverse the change. Electric self-induction is thus analogous to mechanical inertia. An inductance coil, or inductor, tends to smooth out a varying current, as a flywheel smooths out the rotation of an engine. The amount of self-induction of a coil, its inductance, is measured by the electrical unit called the henry, named after the American physicist Joseph Henry, who discovered the effect. The inductance is independent of current or voltage; it is determined only by the geometry of the coil and the magnetic properties of its core. The analogy of an inductor in water pipe terms must include the inertia, magnetic field properties, and geometry coupling properties. Consider the diagram shown below.

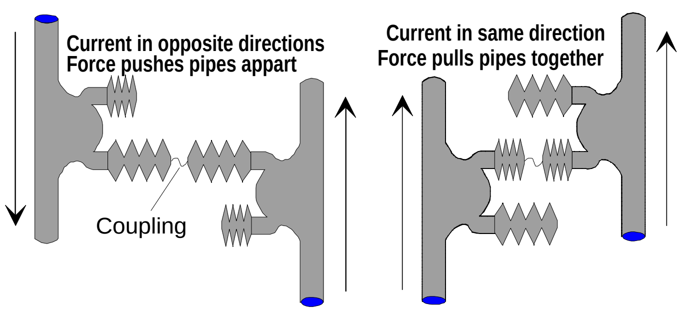


Since inductance is equivalent to inertia our structure contains a flywheel. The affect of the magnetic field that surrounds a wire when a current is flowing is equivalent to the set of bellows attached as shown above. When pressure is placed across this pipe the flow of current will be blocked at first by the flywheel. Slowly the flywheel will start spinning and allow current to flow. As the current passes through the pipe the flywheel spins pushing water into one of the bellows and sucking water from the other. Both bellows are basically springs that want to return to their original positions. The bellows will reach a position where pressure from the spring of the bellows equals the pressure (or suction) of the water and they will stop moving. If the pressure at the input of the pipe is removed the inertia

of the flywheel will create a pressure (suction) to keep the current flowing. Current will also pass from the stretched bellows into the compressed bellows as they return to their original position. This action will also keep the flywheel moving in the same direction to keep current flowing as shown here.



Even a straight water pipe would have inertia or momentum (inductance) due to the fact that the water wants to keep flowing once it is moving. This affect is very small, however, and not totally equivalent to the way an electrical inductor or coil works. Wires that carry currents produce a magnetic field around the wire that will exert a force on other magnetic fields. To make our water pipe analogy work we must tie the bellows to all other water pipes near this one. The coupling can be made in one of two ways, attracting or opposing, as shown here.



This water pipe analogy now contains an inertia device (flywheel), a analogy for magnetic storage (bellows), and an analogy for magnetic field interactions (coupling). This analogy will be used to explain coils, transformers, and other inductive devices such as speakers.

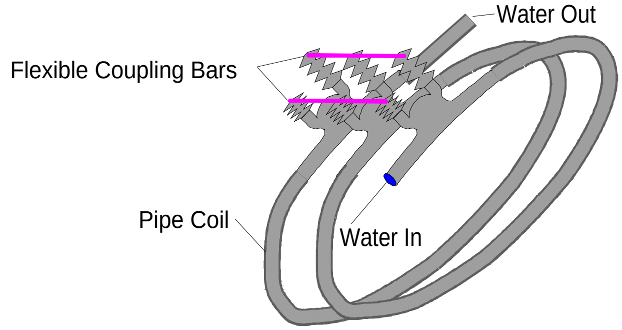
The Inductor Movie.

To see the affect of a simple water pipe inductor with inertia or momentum (inductance) that keeps the water flowing in the same direction click on "Inductor Analogy" on the emailschool course page. Please give this movie 20 to 30 seconds to load. This movie shows only a simple inductor without coupling to other inductors.

Notice how one of the bellows stretches and the other compresses when current first tries to flow. This affect prevents the current from starting instantly. After the bellows are stretched (magnetic field surrounds wires) the current starts flowing. When the switch is turned to stop the flow of current, the bellows return to original position (magnetic field collapses) keeping the current flowing by producing a suction force great enough to force a little current to sneak past the switch. Carefully watch the movie to see the affect of the bellows on producing momentum due to the flowing current.

A Simple Inductor

Early experimenters found that the inductance in a given length of wire increased if the wire is made into a coil. First lets look at our analogy to explain what happens if the pipes are arranged into a coil.



Notice how the coupling bars connect all the compressed bellows together, and all the stretched bellows together. The tighter the coupling the tighter they are connected together and the more they act like one big bellows. This has the affect of increasing the inductance. In other words, all the bellows and flywheels must start up at the same time so the current is held back longer. The longer it takes for the current to get to a desired level, the greater the inductance. Placing certain materials such as iron at the core of the coil has the affect of attaching additional bellows that increases the inductance even more. Other materials, like aluminum or brass, has the affect of loosening the coupling and lowering the inductance. The more turns that are added to a coil the more bellows will link and a higher inductance will result. In electronics the bellows represents magnetic links between wires. As these links are raised by iron or lowered by aluminum the inductance will increase or decrease respectively.

The Mathematics for an Inductor

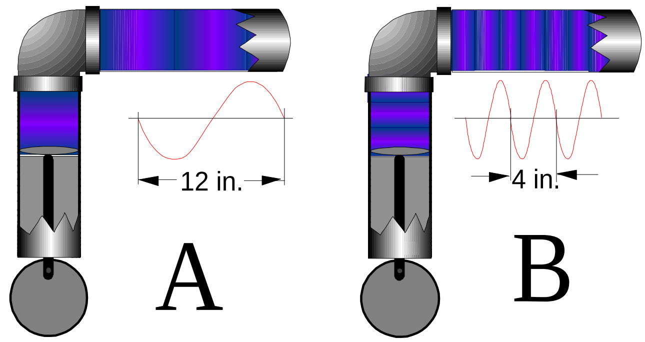
The mathematics for an inductor is actually the same as the mathematics for the capacitor. The only difference is that the time constant is equal to Inductance divided by Resistance (L/R) instead of Capacitance times Resistance (C*R). The other major difference is

that the Inductor equation applies to current and the Capacitor equation applies to voltage.
The time constant is defined as the time in seconds for current (Inductor) or voltage (Capacitor) to fall to 1/e or 36.8% of its initial value or to rise to (1-1/e) or approximately 63.2% of its final value. Where e is the magic number approximately equal to 2.718. Don't worry about the mathematics because the time constant calculator will do the hard work for you. Click on the Time Constant Calculator shown as RC.exe under the Capacitor course and run the program. When the screen appears click on the button in the center marked "L". All the headings should change to match those required for an inductor instead of a capacitor and the button should now have a "C" instead of an "L" as a label. The Time Constant Calculator is now in the Inductor mode. Try calculating different values for resistance and inductance. Keep in mind the only time the inductance graph will be identical to the capacitance graph is when RC = L/R, Vstart = Istart, Vfinal = Ifinal, and the current required = voltage required.

Frequency and Time

Frequency is a term used to denote the number of times that any regularly recurring phenomenon repeats itself in one second. In wave motion, the frequency of the wave is usually given in terms of the number of wave crests that pass a given point in a second. The velocity of the wave and its frequency and wavelength are interrelated. The wavelength is defined as the distance between successive wave crests. In mathematical terms, this relationship is expressed by the equation $v = \lambda f$, where v is velocity (the speed at which the wave travels), f is frequency, and λ is wavelength. From this equation any one of the three quantities can be found if the other two are known.
Frequency is expressed in hertz (Hz); a frequency of 1 Hz means that there is 1 cycle, 1 oscillation or 1 wave per second. The unit is named in honor of the German physicist Heinrich Rudolf Hertz, (1857-94), German physicist, born in Hamburg, and educated at the University of Berlin. Hertz clarified and expanded the electromagnetic theory of light that had been put forth by the British physicist James Clerk Maxwell in 1884. Hertz proved that electricity can be transmitted in electromagnetic waves, which travel at the speed of light and possess many other properties of light. His experiments with these electromagnetic waves led to the development of the wireless telegraph and the radio. In electronics the unit of frequency that is measured in cycles per second was renamed the Hertz; it is commonly abbreviated Hz. Perhaps this

relationship is easier to see if we look at our water pipe frequency generator closely.



Motor speed equals one cycle per second, wave length is 12 inches and frequency of wave is 1 Hz.

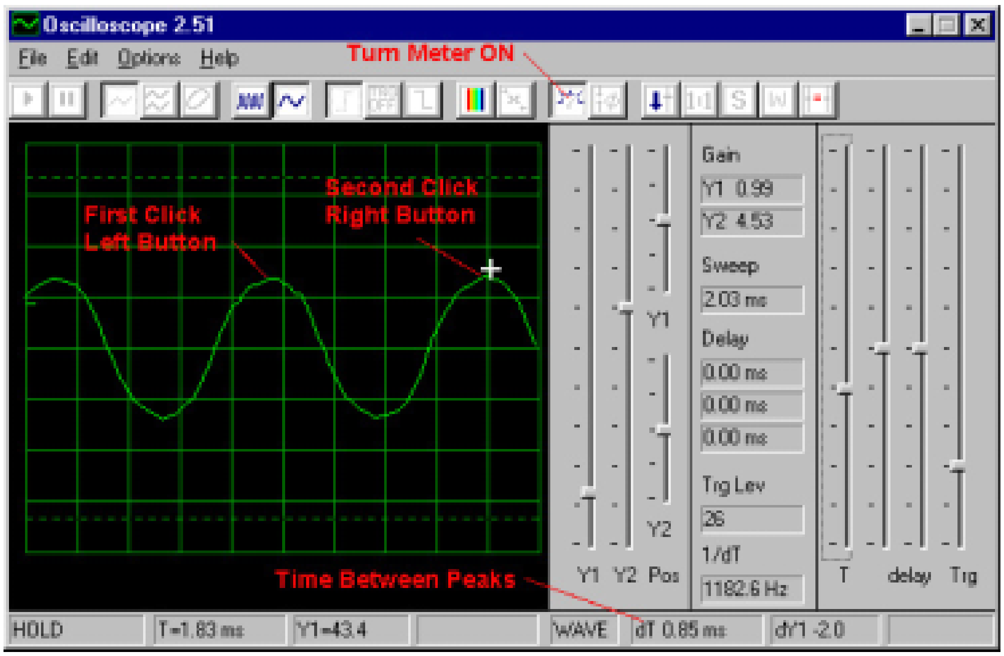
Motor speed equals three cycle per second, wave length is 4 inches and frequency of wave is 3 Hz.

First it is important to realize that the speed of a wave in water is constant. Pretend you are sitting on the shore of a large lake with very calm water. If you tap the water with a stick once every minute you will see the wave move out into the lake and the ripples will be far apart. Now if you tap the water with the stick ten times each minute you would notice that the ripples are closer together (shorter wavelength) but they travel out into the lake at the same speed as the far apart ripples. In other words the shorter wave length does not catch up with the longer ones that were sent earlier because they are traveling at the same speed. In the diagram above the speed of the waves is 1 foot per second. This is for mathematical purposes only and not the actual speed of a water wave.
In our picture above the dark areas are peaks and valleys in the wave. The lighter areas represent the calm water level. The wave travels through the pipe at a constant speed. The only change when the motor rotates three times faster is the distance between peaks is reduced by a factor of three. Another term you must learn is called the period. A period is the time it takes for a wave to complete one cycle. The period of a wave is equal to 1/f. If the frequency of a wave is 3 cycles per second, then the period is 1/3 of a second per cycle. In electronics the electro-magnetic waves that radiate travel at a constant speed just like the water waves. Radio waves, however, travel much faster than water waves. Radio waves travel through space at the speed of light. There is a calculator used to find filter properties called the RLC. exe. Go to the emailschool course website page and open the RLC.exe calculator found under Inductors and coils. The cursor will be in the text box next to the label marked “Frequency”. Type in the number 1000000 for a frequency of 1 megacycle and press enter. Note how the wavelength box has

changed to the number 300. Click on the "EXIT" button to leave the RLC Calculator. The frequency of a wave 300 meters long traveling at the speed of light is one million cycles per second or 1 megaHertz (MHz). The equation used to calculate the frequency of a radio wave is 300000000 (velocity) = 300 (λ-wavelength) X 1000000 (frequency).

Viewing Period on Oscilloscope

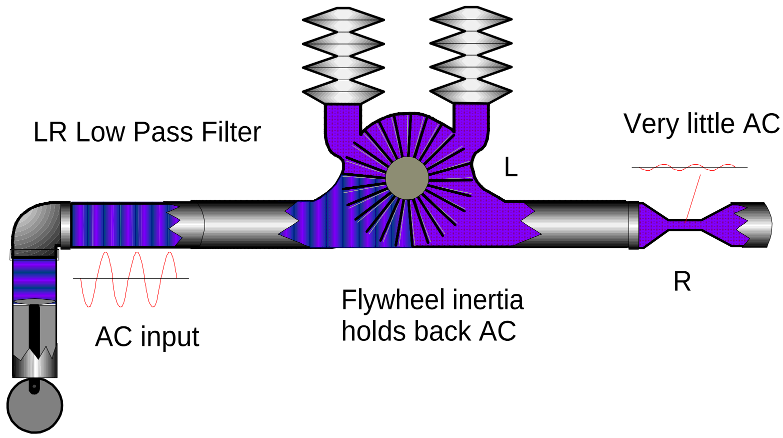
The picture below was captured using a computer scope. The scope probe was placed on the output of a sine wave generator. The generator scale was set close to 1000 Hertz.



The scope meter was turned. The cursor (+ sign) was then moved over the middle peak and the left mouse button was clicked. The cursor was then moved over the next peak and the right mouse button was clicked. The time PERIOD between these two peaks appears in the dT window. In the above example the period is 0.85 ms or .00085 seconds. The oscilloscope display also shows the frequency determined by the period measured. The text box in the display window just above the dT box displays the frequency as 1182.6 Hz. If you take the reciprocal of the frequency you get the period. For example 1/1182.6 = .00084559 or approximately .85 ms.

Inductors used in Filters

A filter is defined as an electronic device used to select or reject currents of specific frequencies. To see how an inductor is used to reject high frequencies lets look again at our water pipe equivalent circuit.



The frequency of the AC input in the picture is too high to pass through the water wheel because the inertia of the wheel and the bellows prevents the wheel from moving instantly. By the time the wheel starts to move it is pulled back by the AC input going negative (suction). Very little amplitude of the AC input makes it to the resistor (R) and other pipes after the inductor (L). If the frequency of the AC signal is made lower, however, the wheel will turn further and more of the AC signal will pass the inductor.
In electronics the inductor acts exactly the same as the water pipe inductor. Open the RLC.exe program on the emailschool.com courses page. When the Calculator screen opens "Click" the button marked LR in the Circuit Configuration Box. The picture should change to show an inductor being driven by an AC voltage source with a resistive load. Click on the frequency text box at the top of the window and enter the frequency of 1000000. When you press the <enter> key the cursor will move to the inductance text box. Enter 10000 in this box and press the <enter> key. The cursor will move to the capacitance text box. Press the <enter> key. The cursor will move to the resistance text box. Enter 1000 for the value of resistance but do not press the enter key. Click on the Recalculate button and the program will enter values for source resistance, source voltage, and load resistance. The program will then calculate the output voltage and Phase with respect to the input voltage. Notice that the Input voltage is one volt but the output voltage is almost 100 times less. Now "click" on the frequency box at the top of the window again, change the frequency to 1000 and click the Recalculate button again. Notice that at this new frequency the output is only down by .2%. Just like the water pipe analogy, the inductor in electronics will block high frequencies but allow lower frequencies to pass.

Inductors in Series

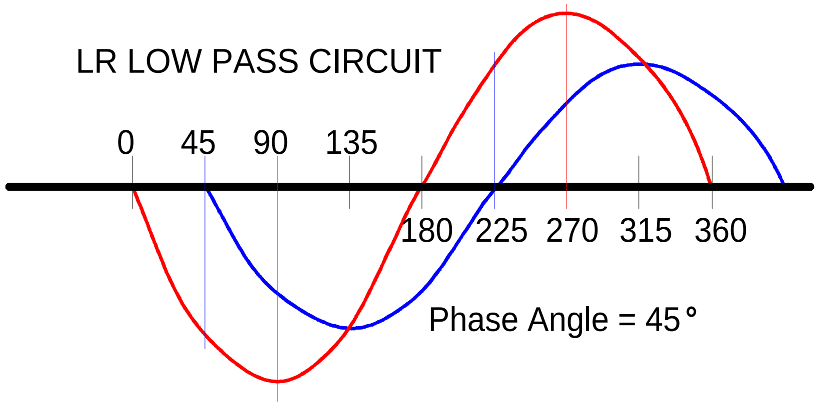
Inductors in series act exactly like resistors in series. You simply add their values to obtain an equivalent value for a single inductor. When using the calculator RinParallel.exe for calculating inductors in series always enter their values in micro-henries (uh), and do not use the K or M multiplier. The answer will also be in micro-henries. Ignore the resistance values and percent error that appears at the bottom of the calculator screen, they are only for resistors.
Open the RinParallel calculator and add the two inductors 10,000 uh and 5,000 uh. Try entering 10,462 uh for L1 and then put 14,563 uh in the "In series" text box. The amount that appears in the L2 text box is the amount needed to get the in series value desired. In other words you need 4,101 uh to get the series value desired.

Inductors in Parallel

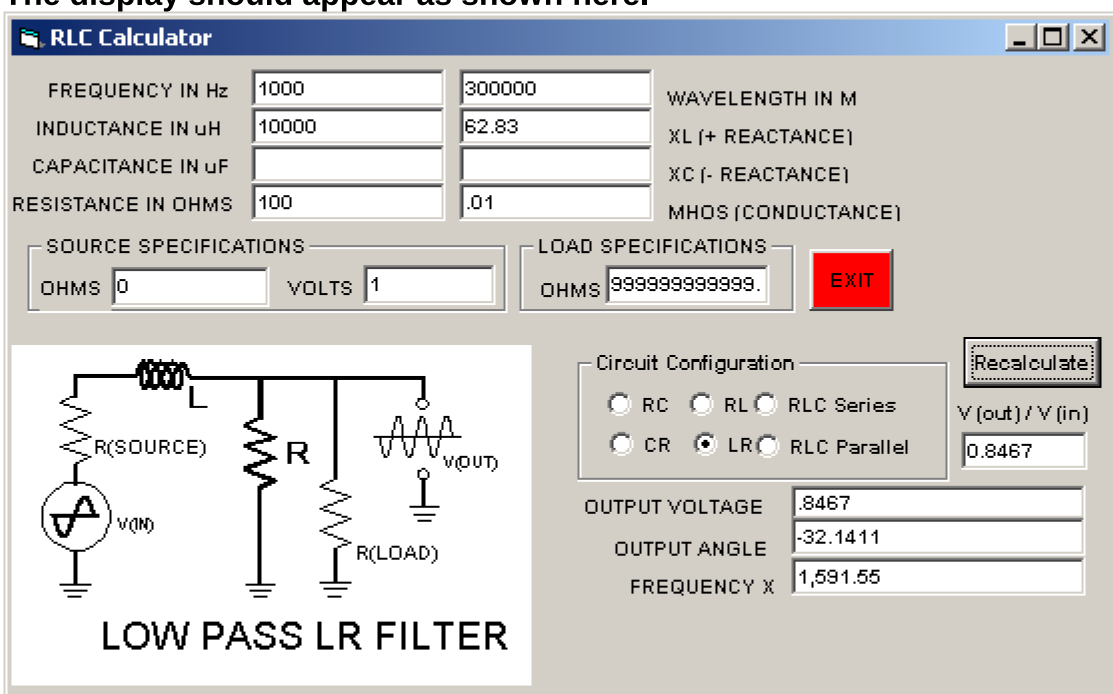
Inductors in parallel act exactly like resistors in parallel. When using the RinParallel.exe program for calculating inductors in parallel always enter their values in micro-henries (uh), and do not use the K or M multiplier. The answer will also be in micro-henries. Ignore the resistance values and percent error that appears at the bottom of the calculator screen, they are only for resistors.
Open the calculator and find the equivalent inductance for the two inductors 10,000 uh and 5,000 uh in parallel. Enter 10,462 uh for L1 and then enter 5,000 uh for L2. The amount that appears in the "in parallel" text box is the equivalent inductance for L1 and L2 in parallel. You may also enter the "in parallel" value to find the inductor needed to lower L1 to the desired value.

Phase Angles

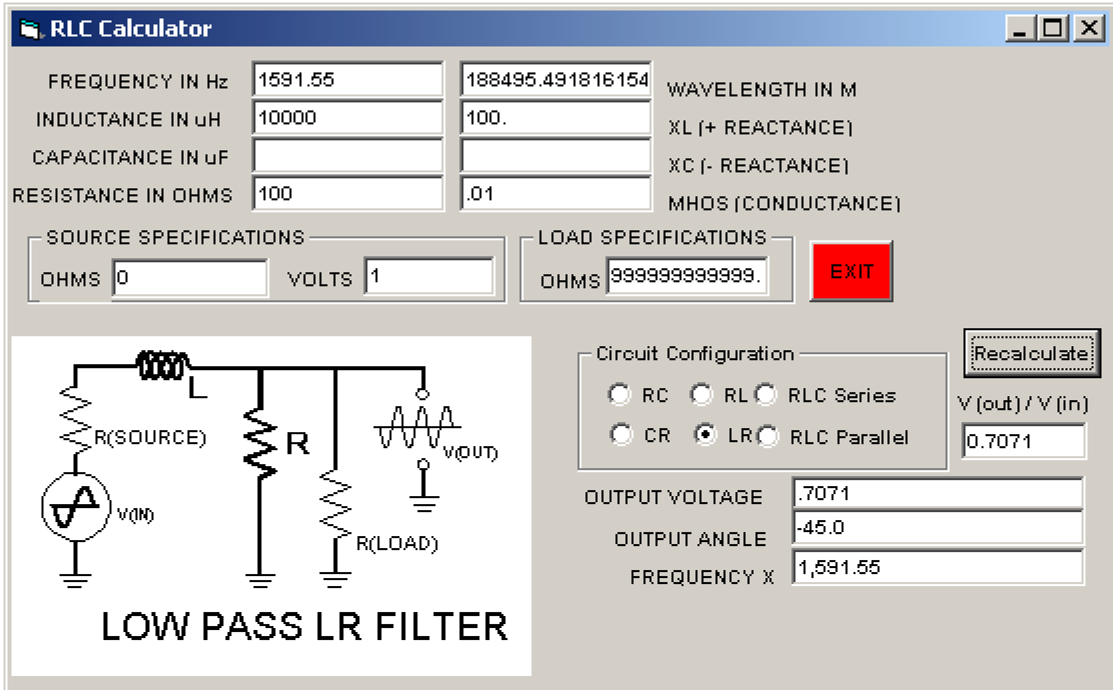
If we take a look at the wheel in the water pipe analogy that drives the piston to make an AC current, it is obvious that the wave cycle consist of 360 degrees of rotation and then repeats. The sine wave in the water that is generated is therefore related to the rotation of the wheel and can be broken down into 360 degrees. The red sine wave in the picture below shows one way of doing this. From zero volts to the first positive peak equals 0 to 90 degrees. From the first positive peak back to zero volts equals 90 to 180 degrees. From zero volts to the first negative peak equals 180 to 270 degrees. From the negative peak back to zero volts equals 270 to 360 (back to 0) degrees. When to different waves are present in the water pipe the rotational delay between their peaks can be described in degrees and is called a "Phase Angle". The Blue sine wave reaches its peak after the red sine wave has advanced by 45 degrees. The voltage peak of the blue sine wave is smaller than the red sine wave by a factor of .707.



Open the RLC.exe tuned circuit calculator and enter the data shown here:
Frequency = 1000
Inductance = 10000
Resistance = 100
The display should appear as shown here.



Change the input frequency box to equal the Frequency X shown in the output area after data is entered and click the recalculate button. The calculator should appear as shown here.



The phase angle now equals -45 degrees. This means the peak of the output voltage is 45 degrees behind the peak of the input voltage. In other words the input voltage will be 45 degrees past its peak before the output reaches its peak. The voltage peak of the output is also .707 times the voltage peak of the input.

Quick Review:

Inductance: Electrical Inertia. An inductance coil, or inductor, is analogous to mechanical inertia smoothing out a varying current, as a flywheel smooths out the rotation of an engine.
Magnetic Field: Whenever current flows a magnetic field is produced around the conductor carrying the current. If the current stops flowing and Magnetic Field collapses in a manner that tries to keep the current flowing.
Coupling: The path through magnetic fields are linked.
L/R Time Constant: The time it takes to change the current to 63.2% of the Maximum Current Level.
Increasing R: Takes less time to reach the current peak.
Increasing L: Takes longer to increase or decrease the current.
90 Degrees: The difference between the current peaks and voltage peaks for an inductor.
RC.exe Time Constant Calculator: A program that calculates time constants and time required to reach a desired voltage (capacitor) or current (inductor).

Filter: A filter is defined as an electronic device used to select or reject currents of specific frequencies.
Period: The period of a wave is equal to 1/f. If the frequency of a wave is 3 cycles per second, then the period is 1/3 of a second per cycle.
Phase Angle: The rotational delay between the peaks of two different waves. One complete cycle equals 360 degrees.
RLC.exe: A calculator program that finds the amplitude and phase output of a filter with respect to its input voltage.

Something to Think About:

What would happen if a current flowing in a coil was interrupted by the instant opening of a switch?

1. Current would instantly stop.
2. The magnetic field would collapse forcing the current to stop.
3. The magnetic field would collapse forcing a voltage to counteract the voltage on the coil and current would stop.
4. The magnetic field would collapse forcing a high voltage to push current through the air to the other side of the switch.
5. The magnetic field would radiate into space at the speed of light as a radio wave when the current instantly stopped.

The red letters in the following sentence spell out the correct number for the answer. Transformers can step up a voltage or current.